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The Intersection of Nanotechnology and Agriculture: Enhancing Soil Fertility and Nutritional Outcomes – A Comprehensive Review

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Abstract

A vast global repository of biodiversity, soil is mostly controlled by soil bacteria. "Nanofertilizers," a novel class of formulations based on nanoparticles, are meant to revolutionize traditional nutrition delivery techniques. Nanoscience has inspired revolutions in peripheral fields through promising methods like nano-pesticides, nano-sensors, nano-magnets, nano-films, nano-filters, and nano-nutrients. This allows for improved input management and conservation, which makes it possible to boost agricultural output. Their main features, like their huge surface area, controlled release mechanisms, and specially designed nutrient encapsulation, provide several advantages for optimizing plant nutrient uptake. Despite the fact that agriculture is a broad subject, the use of nanotechnology in this industry has increased over the past decade due to public interest and the field's modest rate of expansion. By activating soil enzymes, nanotechnology improves soil fertility and nutrient transfer. Nanomaterials (NMs) and rhizospheric bacteria can work together to enhance soil health and plant growth. Together, nanotechnology applications provide a comprehensive strategy for controlling plant nutrition and health, enabling a reduction in chemical inputs and the harm they do to the environment. Nanosensors can monitor soil and plant health in real-time, allowing for more accurate and efficient crop management. NPs can also improve the delivery of nutrients and pesticides to plants, reducing waste and increasing effectiveness.

Keywords: Nanofertilizers, Rhizospheric, Nanotechnology, Nanomaterials, Biodiversity, Soil Health, Plant Nutrition

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INTRODUCTION

In addition to being a living system, soil contributes negatively to the Earth's ecosystem. The ability of a soil to function as a living system that maintains and improves plant and animal growth and productivity within ecological and land-use limitations is referred to as soil health. More precisely, it refers to a soil's capacity to recover harmful materials from the soil, support or improve nutrient cycling, potentials for transport and retention of water and solutes, as well as chemical and physical stability. Nanotechnology considers and controls the matter's size, which is approximately between one and one hundred nanometers.[1] Certain characteristics of bulk materials, such as their electric conductivity, dimension, piercing force, temperature of melting, and physical strength, and many more, change when they are reduced to nanoscales, opening up new possibilities.[2] Agricultural production is increased by improving the genetic composition of plants through crop modification and delivering genes and molecules through advancements in nanotechnology. With the advancement of appropriate methods and technologies for precision farming, natural resource management, advance food item tampering and disease detection, and efficient agrochemical delivery systems, such as those for fertilizers and pesticides, the possibility of contamination is growing.[3] Nanotechnology is essential to the agricultural sector because it helps reduce nutrient losses from traditional fertilizer application at the farm level, ensuring food security and a healthy diet.[4] According to Zhao *et al.*,[5] the use of nanotechnology enhances soil fertility and nutrient transport by stimulating soil enzymes. *Rhizospheric* bacteria and nanomaterials (NMs) can work together to enhance soil health and plant growth. One of the reasons NMs are so prevalent in the rhizosphere is the usage of industrial covered NMs-based products, such as nano-fertilizers.[6] According to Chaudhary *et al.*,[7] it has been demonstrated that this benefits the soil's microbes by altering rhizospheric microbiome characteristics as well as plant development, production, and yield quality. The rhizosphere's activity and soil structure are impacted when NMs are added to the soil ecosystem.[8,9] Tian *et al.,*[10] declare that the type of microbial species that live in the soil, the circumstances of the soil, and the properties and concentration of NMs can all affect the overall impact of NMs on the soil microbiome. Therefore, when applied in a controlled manner with respect to application dose, exposure period, types, and sizes of generated NMs, NMs may be beneficial to plants and soil bacteria.[11] Since the field of applying nanonutrients is still developing, a variety of nanoparticles have been effectively used as macro and micronutrients to increase soil fertility, crop nutrient uptake, and production.[1] Because there have been instances of NP toxicity in plants, the dosage of nanoparticles is optimized to enhance growth and development. The synthesis of NPs is done from organic/natural sources that are readily biodegradable. The function and processes of various NPs as fertilizers in improving agricultural production and soil fertility, and also the harmful and normal limits necessary for sustaining soil health, are thoroughly examined in this book chapter. Examples include targeted nutrient delivery to crop plants to improve soil hydrophilicity and gene editing for biotechnological applications.

The function of nanofertilizers in soil

NFs are applied through soil irrigation, which guarantees two benefits: Enhancing the soil to increase the productivity of plant development[12] because plants might not be able to use bigger amounts of inorganic fertilizers when they are applied to agricultural land.[13,14] Because NPs are smaller and have a higher surface area compared with volume proportion, NFs may be more effective for root systems to absorb nutrients, increase photosynthetic efficiency, and increase the capacity of seeds and seedlings to absorb particular light wavelengths through light-dependent reactions.[5] Numerous edaphic parameters regulate the range of mineral elements in the soil and can also change microbial communities and rhizospheric biological biomass in order to increase soil fertility,[15,16] crop development with the availability of water.[17] According to Taiz and Ziger,[18] the primary location for the ecophysiological relationship between plants and soil is the rhizosphere. As it aids in the absorption of water and nutrients, soil erosion, nutrient availability, pH, and texture all affect and hinder root growth (Figure 1). Through the processes of mass flow and diffusion, where a concentration gradient is created and the movement occurs through xylem (solute distribution regulated by transpirational pull), nutrients are transferred from the soil to the aerial portion of the plant.[19] According to Mittal *et al.*,[20] Numerous absorption/uptake channels, such as the apical emerge, roots, grains, connecting environmental elements, cell membrane rigidity, and the physiological in nature, structural, and biochemical functions of the plant species/cultivars, are associated with the creation of nanoparticulates. According to Adisa *et al.*[21] NPs' higher surface tension on fertilizer particle surfaces than that of regular fertilizer efficiently control nutrient emit. The apoplastic pathway can be changed to the symplastic path, which is a more controlled and ordered manner for NPs to move through the crop-plant shape, perhaps avoiding the problem of the Casparian strip preventing NPs from moving radially within the root's endodermis. The apoplastic route is necessary for the body to absorb and use NPs.[7] Metal nanoparticles (NPs) can penetrate seeds and migrate into seedlings to stimulate plant development through seed priming, as noted by Seleiman.[22] NFs can release nutrients gradually on their own or in combination with organic or synthetic fertilizers. While complete nutrient release may take 40 to 50 days, synthetic fertilizers yield the same result in 4 to 10 days.[22]

Nanoparticles' function in soil restoration

The solid, liquid, and vapor realms that make up soil as a natural entity interact at various scales to produce a variety of ecological goods and offerings. These realms are mediated by organic-carbon-mediated domains. Soil health, functionality, and quality are significantly impacted by soil organic carbon. The nutrient cycle, carbon transformations, and soil structure preservation are important factors in preserving soil health.[23] The primary factors of these characteristics are the metabolic process and microbial activity. NM applications may stimulate this activity, which could lead to increases in the health and fertility of the soil. Microbes and soil animals interact to determine soil fertility and productivity, since soil biodiversity has been suggested to be the main factor controlling soil health. Graphene oxide and carbon nanotube-treated soils showed a decrease in soil enzyme activity, but microbial biomass remained relatively unaffected.[1] Intensive farming is causing severe damage to soil biodiversity. With the new optimism, nanotechnology, one of the most significant inventions of the twenty-first century has the ability to improve conservation and management methods, reduce waste from agricultural inputs in various environmental contexts, expand existing agricultural practices, and facilitate sustainable development.[25] By creating more climate-resilient farming systems and repairing damaged soil,

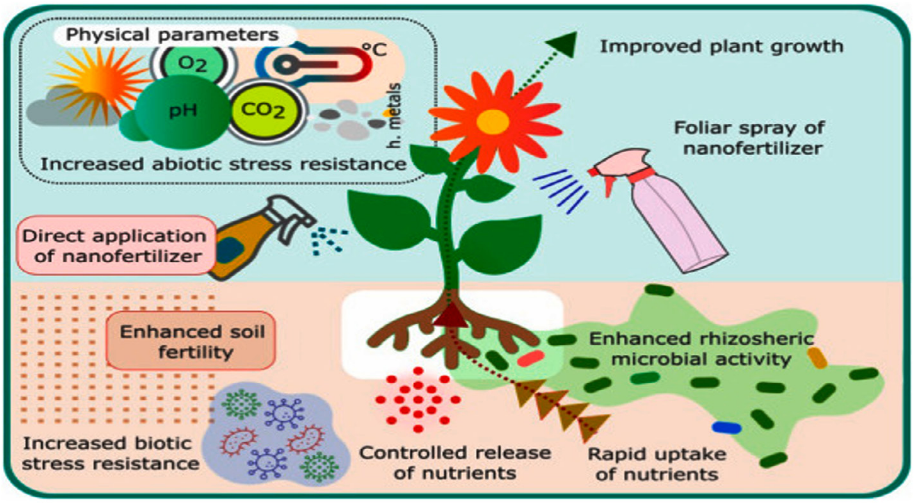

Figure 1. An outline of how soil uses nano-fertilizers[24]

nanotechnology enhances the activities of animals and soil microbes in addition to various agricultural practices that enhance soil health. Crop output is negatively impacted by elements of soil stress that could impair plant performance, such as brine, lack of moisture, low pH level, insufficient root zone temperature, nutrient availability, and proper biological community functionality.[26] Furthermore, to improving soil health, the unique land microbiome created by nanotechnology will increase crop yields. Figure 2 shows the schematic representation of plant development that is created under unfavorable soil conditions by microorganisms attached to roots that use NMs to trigger nutrient cycling and phytostimulation.[27]

Nanotechnology-assisted soil microbiome manipulation for better sustainability of the soil

The phrase "crop microbiota" describes all of the microorganisms that live on different parts of crops. These organisms, which are regulated by root fluids, exist in the rhizoplane and phyllosphere,[28,29] and are affected by a variety of elements, including plant type, secretions, environmental factors, physicochemical characteristics, and soil microbial abundance. Among the many widely acknowledged plant support services that bacteria provide are nutrient fixation, nutrient mobilization, micronutrient sequestration, effector chemical synthesis, Mechanisms of resistance and protection against diseases of plants.[30]

The functioning and flexibility of the soil microbiome must be studied in this era of climate change since it can change to support plant and soil health or perform better. According to Jansson *et al.*,[31] The biogeochemical cycle of macro and micronutrients depends on the growth of soil and plant microorganisms. Microbes that supply nutrients to host plants include mycorrhizal fungi and rhizobia, a diazotrophic bacterium that produces root nodules in legumes.[32] Understanding how NMs and plant growth-promoting rhizobacteria (PGPR) interact in the rhizosphere, however, may offer a wonderful opportunity to investigate inexpensive, eco-friendly nano-formulations for use in agriculture.[33] It also helps to transform transforming unavailable soil minerals into plant-useful forms by inhibiting pathogen activity and lowering biotic and abiotic stresses.[34]

Nanotechnology's function in mitigating plant growth under soil distress

Soil stressors such as salt, thirst, compaction, drought, acidity, suboptimal root zone temperature, nutrient availability, soil types, and soil biota functionality all impair plant performance. These strains can be sustainably primed by utilizing modern innovations, especially nanotechnological techniques and nano-enabled products.[1] According to studies, applying carban-based NMs improved soil fertility by inducing soil enzymes and increased *Z. mays* growth by

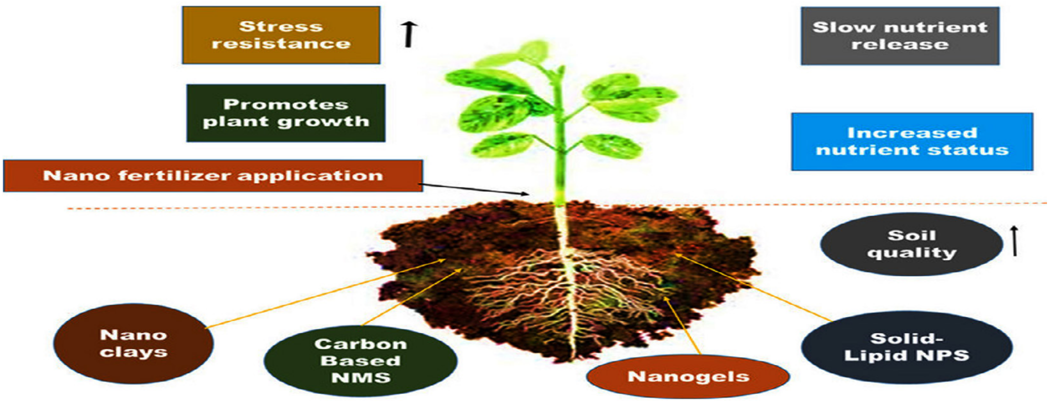

Figure 2. By increasing nutrient cycling and root-associated microbial functions, nanotechnology can drive plant development in unfavorable soil circumstances[35]

enhancing nutrient uptake.[5] According to an experiment by Lin *et al.*,[36] metal-based NMs such Fe, Cu, Co, and ZnO enhanced Glycine max growth when drought stress was present. Se-based NMs are used to induce high temperature stress in Sorghum bicolor. Through root secretion, a variety of microorganisms that resemble *Brevibacterium frigoritolerans*, *Bacillus thuringiensis,* and *Bacillus velezensis* reduce NaCl stress.[37] The effect of salt on plant growth is lessened when Si-Zn NMs and microorganisms that promote plant growth are applied together.[38]

Nano fertilizers

Through the use of nanotechnology, effective fertilizers with a slow release could be developed. Formulations using nano-fertilizer may improve nutrient consumption effectiveness in greenhouse conditions. In addition to protecting crops from bacterial and fungal diseases, these nano.

The leaching of these nutrients from the soil has resulted in a significant decrease in soil fertility. This is primarily due to the relatively low nutrient utilization efficiency of conventional fertilizers, which is around 30-35% for nitrogen, 18-20% for phosphorus, and 35-40% for potassium[39] (Figure 3).

Formulations, which can also be called nano-pesticides, may also have unforeseen consequences for non-target plant-associated microorganisms that are essential to plant nutrition, such as bacteria that fix nitrogen or mycorrhizal colonies. Furthermore, this broad-spectrum antimicrobial treatment could have adverse effects on the helpful soil bacteria that decompose organic matter (OM), which sustains soil quality over time.[1] Mesoporous

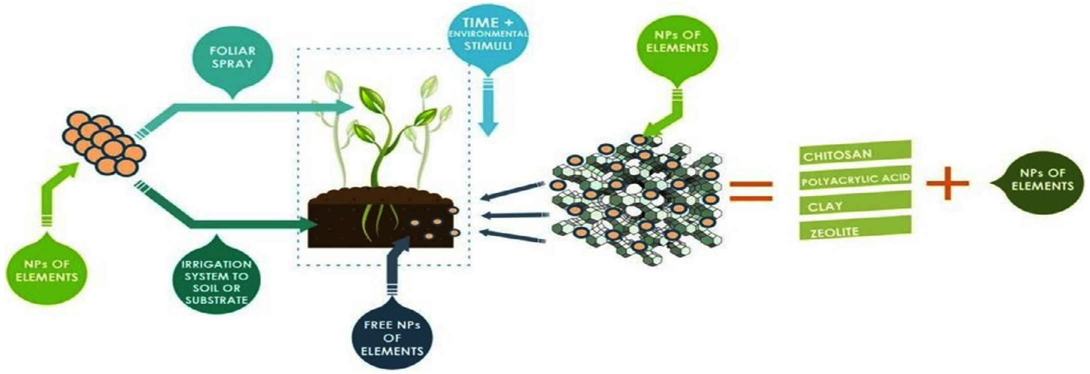

Figure 3. Nano-coating works through several mechanisms, mainly focusing on controlling the release rate of nutrients to the plants[39]

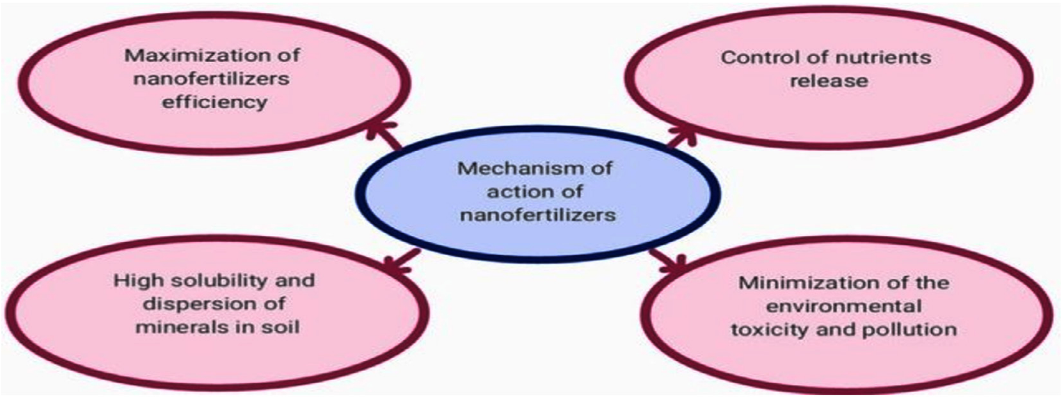

Figure 4. Mechanism of action of controlled nutrient release nanofertilizers in the field[39]

aluminosilicate-based nanoparticles (NPs) have demonstrated great potential for a regulated and efficient release of macro- and micronutrients in soil to improve plant growth and yield, in contrast to their mineral salt counterparts. For instance, applying a nanoscale Mn-carbonate hollow core shell system to rice in both aerobic and submerged settings produced a gradual and consistent release of zinc, in contrast to $ZnSO_4$. Likewise, concurrent application of SiO_2-TiO_2 NPs enhanced nitrate reductase activity, which in turn enhanced the absorption of nutrients by soybeans. Rui *et al.,*[40] observed that applying iron oxide nanoparticles (Fe_2O_3-NPs) compared to applying chelated form of iron, this led to higher nutrient absorption, which in turn increased peanut plant growth and productivity. Despite all of these findings, microencapsulation still outperforms nano-encapsulation for traditional chemical fertilizers, therefore more research is necessary to produce efficient and reasonably priced encapsulated nano-fertilizers. In this way, NPs can be covered with chemical fertilizers, which create a thin layer of protection around the fertiliser capsule. Because it would allow fertilizers to be released gradually and evenly, the use of this barrier protective layer would increase the efficiency of nutrient consumption.[1] According to Ditta *et al*.,[4] For improved absorption and nutrient usage efficiency, conventional synthetic fertilizers can also be enclosed in nanoporous substances, which would guarantee a consistent and gradual release of nutrients.

According to Subramanian and Tarafdar,[39] In addition, controlled-release fertilizers can improve the environmental sustainability of agriculture by reducing the release of nutrients into the environment (Figure 4).[39]

Types of nanofertilizer

Nanofertilizers have been classified into three groups:

i. Nanoformulation of macronutrients
ii. Nanoformulation of micronutrients
iii. Nutrients-loaded nanomaterials

Nanoformulation of nacronutrients

Nitrogen nanofertilizer

The most important nutrient limiting worldwide agricultural production is nitrogen. Despite several efforts, farming's nitrogen usage efficiency is still around 50%.[41] Nitrogen nano fertilizers combine nitrogen molecules with graphite, metal oxides, and carbon nanotubes. According to one study, which looked at the nitrogen-containing nanofertilizer formulations' pattern of nutrient release, standard fertilizer only lasts 300-350 hours, but the nutrients supplied by nanofertilizer last up to 1200 hours.[1] To improve the efficiency of N utilization, another study recommends applying zeolite as a nanofertilizer.[42] Higher N accumulation, less N leaching and volatilized losses, and improved soil pH and moisture are all signs of zeolite-based nitrogen nanofertilizer.[43] The findings indicated that the urea generated from nanohybrids with a hydroxyapatite to urea ratio of 1:6 released urea 12 times slower than that of pure urea. Additionally, nearly as much accessible nitrogen was present in the nanohybrid as in pure urea.[4] Slow and unrestricted release of NH_4^+ from the zeolite's internal channels enables the crop to absorb it gradually, increasing the formation of dry matter.[1]

Phosphorus nanofertilizer

One of the essential minerals for plants to develop and flourish is phosphorous. In an experiment with maize plants, Adhikari *et al.,*[44] found that using nano-rock provided phosphorous consumption as superphosphates at a lower cost. Nanoformulations of hydroxyapatite (nHAP; $Ca_{10}(PO_4)_6(OH)_2$) are employed to provide crops with phosphate, according to Tang *et al.*[45] Priyam *et al.*[46] reported that when sprayed in the right amount, it improves the absorption of phosphorus and other nutrients by plants.[46] One study found Plant growth and yield were enhanced when a rock phosphate-based nanofertilizer was applied to damaged soils, particularly when the phosphate-based nanofertilizer was encased in a chitin shell.[45]

Potassium nano-fertilizer

A recent advancement in agricultural technology are potassium nano-fertilizers, commonly known as nano potassium. The minuscule particles that make up these nano-fertilizers enable them to enter the soil and rhizome region more deeply, increasing the rate at which the vital nutrients are efficiently absorbed. Nano-potassium is more resistant to leaching, able to dissolve in water, and less likely to be carried away by irrigation and precipitation, according to Sheoran *et al.*[47] Nanofertilizers based on potassium are good at maintaining increased yields over time. Exogenous treatment of Nano-K enhances the leaf area with increased no. of leaves, index of harvest, the amount of chlorophyll, disease and pest resistance, grain yield, overall yield, and K %.[1]

Calcium nano-fertilizer

According to Carmona *et al*.,[48] of calcium-based nanofertilizers, including calcium carbonate, calcium nitrate, and calcium phosphate, are useful for enhancing the quality, crop development, and fruits yield, vegetables, cereals, and pulse crops. Additionally, they provide defense against living and non-living stressors.[48] Calcium phosphate (CaP) nanoparticles have drawn interest recently as potential major-nutrient nanofertilizers that may be more effective at using nutrients than conventional fertilizers.[48] They may also be altered to incorporate more macronutrient-containing materials, like urea or nitrate, due to their enormous surface area, creating nanofertilizers with improved nitrogen-releasing capabilities. Research has demonstrated that CaP nanofertilizers outperform traditional fertilizers in agricultural settings.[49] Biomedical applications have made use of biomimetic calcium phosphate nanoparticles (CaP) because they are biocompatible and biodegradable. Because of this, precision farming has made relatively little progress to distribute active species to plants in a controlled manner. In order to create multi-nutrient nanofertilizers (nanoUNPK), A study outlines a low-cost and environmentally friendly synthetic method for doping CaP with potassium and nitrogen. These gradually released essential plant macronutrients (NPK) can be used to reduce the amount of nitrogen supplied to durum wheat by forty percent contrasted with the traditional implementation. with no affecting the final kernel weight per plant.[50]

Sulfur nanofertilizer

In addition to sulphur-based compounds similar to sulhur-coated urea or sulphur-coated potassium sulphate,[51] which are slow-release fertilizers, sulfur-based nanofertilizers also contain elemental sulfur. Because the coating is stable, the rate of dissolution is slowed, allowing the fertilizer to be released gradually. According to Ragab and Saad-allah's 2020 projection, applying external sulphur nanofertilizer to the soil enhances sulphur metabolism and lessens the negative impacts of manganese stress.

Nanoformulation of micronutrients

Iron nanofertilizer

Across a wide pH range, iron chelated nanofertilizer provides delayed iron release and is incredibly durable. Askary *et al*.[52] hypothesized that iron oxide nanofertilizer at a concentration of 30 M significantly raises growth indicators, total protein content, and photosynthetic pigments. Iron is mostly absorbed by plant roots as Fe^{2+} and chelated iron, with very little Fe^{3+} being absorbed. In plants, iron is an essential component of a substance that binds to chloroplasts that and influences photosynthetic and a number of redox processes via electron transfer. According to Taskin *et al.*,[53] nano-iron fertilizers have the ability to increase plant iron levels and may even replace other sources of iron.

Zinc nanofertilizer

Plants primarily absorb zinc as Zn^{2+}, which is necessary for auxin production and development. Nano-sized zinc oxide (ZnO) can enhance plant development more than traditional zinc fertilizer by increasing plant dry mass, subsidiaries, root length, and height ($ZnSO_4$).[54] Additionally, a number of researchers have discussed and tested more efficient nanoscale ZnO concentrations for different plants.[55]

Copper nano fertilizer

Nutrients are effectively transported to plants using copper nano-fertilizers. Copper nanoparticles are extremely safe to use, enter plant cells, and supply the root system with essential nutrients. Furthermore, they are less likely to leach and can be used sustainably to increase the yield of field crops like wheat and maize. They are also not susceptible to runoff or leaching, which makes them a great option for sustainable agriculture because they increase root length, improve stress tolerance, provide resistance to pests and diseases, and increase the amount of protein in starch degradation.

Manganese nano fertilizer

The roots absorb a form of manganese nanofertilizer called Mn^{2+}. Mn affects the uptake and utilization of N, helps convert NO_3^- to NH_4^+, affects plant respiration and photosynthesis, and is essential for the plant's electrochemical process. Plant growth, yield, branch and root elongation, and nutrient content are all impacted by nanoparticle nutrients, which are more readily absorbed and utilized by plants than conventional fertilizers. However, the results of various application techniques vary. According to Yadav *et al.*,[1] spraying nano-manganese on leaves has a greater effect than applying it to the soil.

Boron nano fertilizer

Singh *et al.*,[55] reported that a micronutrient that is often lacking in soils, although it is necessary for the best possible growth and development of crops-plant. This boron deficiency is mitigated by boron-based nanofertilizers, which give crops a more targeted and concentrated boron supply. In boron-based nanofertilizers, borate is mixed with a variety of other substances, like humic acid, which is used to produce NPs. After that, they remain in a fluid or firm form and used as a spray for foliage on the crop or soil. The nanofertilizers based on boron have the ability to penetrate plant cells and deliver vital micronutrients.[55] According to Davarpanah *et al.*,[56] pomegranate fruit output and quality are improved by exogenously applying smaller dosages of zinc and boron nanofertilizers. When nano-Zn and nano-B chelate fertilizers were applied prior to full bloom, the concentrations of both microelements in the leaves increased. Effect of nano materials on crop growth, yield and yield attributes on different crops is shown in the Table.

Biofertilizers-based nano fertilizer

Using biofertilizer-based nanofertilizer, the coexistence of biocompatible nanomaterial and biological sources highlights the gradual release feeding nutrients to the crop from the soil shoots via root xylem for a long duration, promoting and increasing crop productivity and yield.[57] According to Thirugananasambandan's 2019 hypothesis, nano-carriers provide long-range fertilizer availability at different stages of plant development, enhancing both field performance and financial expenditure. The PGPR raises the nutritional value of soil by Phosphate solubilization, siderophore production, and fixation of nitrogen. Nutrient fertilization is essential for preserving soil fertility and raising the profitability of crops. In recent decades the application of chemical fertilizers has grown increasingly necessary to maintain the productivity of modern agricultural practices. Conventional fertilizers' significant water loss and low nutrient utilization efficiency are their main disadvantages. Nanotechnology is a flexible tool used in agriculture to increase plant development, growth, and output. Nanotechnology makes it possible to increase agricultural output by increasing input efficiency and lowering pertinent losses. Nanotechnology has grown in importance as a topic of study due to its numerous uses in agriculture, especially the application of nano-agrochemicals to increase agricultural productivity and fertilizer usage efficiency. The availability, absorption, and efficiency of plant nutrients are improved by nanobiofertilizers, which combine beneficial microbes with natural products (NPs). The microbes aid in nutrient solubilization, mineralization, and fixation, while the NPs' tiny size and large surface area enable them to deliver nutrients to plant roots and tissues effectively.

Benefits of biofertilizers-based nano fertilizer

Nano fertilizers based on biofertilizers are a novel way to increase agricultural sustainability and output. These fertilizers combine the advantages of nanotechnology and biofertilizers, which contain living microorganisms. Below is a summary of the main advantages:

Benefits to crops

Enhanced Absorption of Nutrients Improved absorption

By increasing the fertilizer's surface area, nanoparticles can improve plant uptake and nutrient availability.

Table. Effect of nano materials on crop growth, yield and yield attributes on different crops

Crop	Nutrient	Nanomaterial used	Experimental Conditions	Effects	Ref.
Wheat	Fe	nZVI	Various iron sources ($FeSO_4$, Fe-EDDHA, and nZVI, 0.2%) applied topically	The iron content of grains was markedly raised by N-ZVIand urea. We will probably be an alternate supply of iron after n-ZVI	Millan *et al.*[58]
	Mn	Manganese Nanoparticle	Growing soil and applying foliar spray	Manganese, phosphorus, and potassium levels in plants were reduced when nano-manganese was added to the soil, whereas manganese levels in branches and grains were raised when leaves were exposed	Dimkpa *et al.*[59]
Maize	K^+	Potassium nano-silica (PNS)	PNS concentrations of 0, 100, and 200 ppm in addition to foliar spraying and irrigation (-0.03, -0.6, and -1.2 MPa)	The amount of inorganic nutrients in seeds under drought stress increased when PNS was applied. PNS mitigated the negative effects of drought stress	Aqaei *et al.*[60]
	Zn	Zinc Oxide Nano Particles	$ZnSO_4$ concentrations of n-ZnO particles in suspension form (0, 0.05, 0.5 ppm) are equal to those of the control group.	Plant dry weight increased when nano zinc was applied. In comparison to the control, the plant height increased to 59.8 cm, the root length increased by 1.6 times, and the branch zinc content increased to 37 ppm	Adhikari *et al.*[52]
Soybean	P_2O_5	Synthetic apatite nanoparticles	The following fertilization methods are available: tap water, synthetic fertilizer containing regular P, synthetic fertilizer devoid of P, and synthetic fertilizer including NHA	In soybeans, synthetic apatite nanoparticles increased the seed production and growth rate by 20.4%. Both subsurface and aboveground biomass grew by 41.2% and 18.2%, respectively	Liu *et al.*[61]
Peanut	Zn	Nanoscale zinc oxide (ZnO)	ZnO suspensions with 400, 1000, and 2000 ppm concentrations were made	While an excessive concentration can restrict plant growth, ZnO nanoparticles can transmit zinc to plants, improving seed germination, root length, branch dry weight, and pod production	Prasad *et al.*[62]
Cowpea	Cu	25 nm or 60-80 nm nano-Cu	Plants were exposed to four levels (0, 125, 500, and 1000 mg/kg) of nano-Cu for 65 days	The absorption effect of copper at the nano-copper level was more significant than that of the control group	Ogunkunle *et al.*[63]
L. multiflorum	N	Clinoptilolite-NH4Clinoptilo-lite-urea	treated on sandy loam soil with 0, 60, 120, and 180 kg/ha of nitrogen	The efficiency of nitrogen uptake and yield both markedly increased	Millan *et al.*[58]
Lettuce	N	Nano nitrogen (n-N)	Drip irrigation and surface irrigation combine bulk size nitrogen (b-N) and nano nitrogen (n-N)	In addition to improving nitrogen absorption and utilization efficiency, the combination of 75% n-N drip irrigation and 25% n-N foliar spraying had a substantial impact on plant biomass, crude protein, and yield	Sharaf-Eldin *et al.*[64]
	P	Synthetic nano-hydroxy-apatite (NHA),	greenhouse with natural light. 200 mg of basal N (from NH_4NO_3) and 200 mg of P per kilogram of soil	NHA is more efficient for lettuce plant growth and can raise the dry weight of lettuce plants more than H3PO4-P (soluble phosphorus)	Taskin *et al.*[65]
Portulaca oleracea L.	Fe	Fe (III)-amino-levulinic acid nano chelate.	N-Fe (ALA)3 and Fe-EDDHA were sprayed with Fe at a dosage of 0.1% and 0.2% (w/v) for foliar application	Fe (III)-aminolevulinic acid nano-chelates applied topically can raise the amount of Fe, Zn, N, Mg, Ca, and K in the aboveground portion and accelerate purslane plant growth	Tavallali *et al.*[66]
Thankan	Ca	Calcium carbonate nanoparticles	Field tests. 95% WP, 26% SC, and CK	Although excessive Ca spraying may affect the potassium content, the calcium concentration in leaves treated with nano-Ca increased 13 times when compared to the control group	Hua *et al.*[67]
Peaches	Mg	Magnesium particles are less than 900 nm	fertilizing through foliar means. Use an automated sprayer to apply 500 kg/ha of diluted magnesium to 10 trees every treatment	When the plant nutrients' particle size was decreased to less than 900 nm, the peach's petiole, front, back, and leaf side all had higher magnesium contents following treatment	Park *et al.*[68]

Targeted delivery

By designing nanoparticles to release nutrients gradually, it is possible to give plants a consistent supply of vital components over an extended length of time.

Sustainability of the Environment Decreased chemical runoff

Nano fertilizers based on biofertilizers are usually more effective, requiring less fertilizer to produce the same effects, thereby lowering pollution levels in the environment and Less toxicity to using bio-based ingredients improves soil health and biodiversity.

Increased microbial activity support soil microorganisms

By fixing nitrogen, breaking down organic matter, and improving soil structure, the helpful microbes found in the biofertilizers in these nano fertilizers contribute to better soil health.

Encourage plant growth

In addition to boosting productivity and enhancing disease resistance, beneficial microbes can also stimulate plant growth hormones.

According to Sharma *et al.*,[69] the organic components used in nanobiofertilizers are essential for the primary processes of Soil nutrient replenishment, phosphate solubilization, and nitrogen fixing. Furthermore, a steady delivery of nutrients to crops is guaranteed by the covering of nanoparticles, which uses nanomaterials mainly polymers, zeolite, and chitosan.[70] These nanoparticle-coated biofertilizers' unique properties aid in crop fertilization and the steady supply of nutrients that plants can absorb. These features include increased reactivity, surface area, and nano size. According to a study on the effects of biochar, nano biofertilizer, and vermicompost on the growth of *Echinacea purpurea* L., the combination of vermicompost and nano biofertilizer treatments produced the highest fresh and dry root weights in the plant.[71] In another study, Fe-carbon acylated homoserine lactone-coated nanofibers and bacterial endospores in activated carbon beads were mixed to produce a lightweight nanocomposite biofertilizer.[72] After 30 days, the nanofertilizer dramatically raised the biomass, root length, chlorophyll, and protein levels of both leguminous and non-leguminous plants.[72] It seems to be safe to use nanoparticles in combination with microorganisms to create nano biofertilizer.

CONCLUSION

Based on the foregoing discussion on nano-fertilizers, it has two main effects: they halt the distribution of essential nutrients and extend the fertiliser impact time frame. Nanotechnology undoubtedly has the ability to significantly impact the economy, energy, and environment via improving fertilizers. As a result, nanotechnology has enormous promise for sustainable agriculture. There are currently more opportunities to reduce costs, increase input use efficiency, and slow down environmental degradation through the use of nano-fertilizers. Thus, the potential for choosing the use of nano-fertilizers in farming practices in the twenty-first century in order to preserve soil health and environmental quality, boost crop productivity, and encourage the use of nanosensors for soil microbial activity and nanoparticles in fertilizers. In order to feed the expanding population while facing ever-increasing constraints on natural resources, the integration of NMs (Nano-Materials) with agricultural farming systems holds great promise for addressing the growing global concerns of safety for soil wellness, crop productivity, food safety, sustainability, and climate change.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTION

UM, SG, SS, ASY, KY and RaviK conceptualized the study. SG, ASY, KY and RaviK designed the study. BA performed analysis and data interpretation. SG wrote the original draft. SG and RavinK reviwed and edited the manuscript. All authors read and approved the final manuscript for publication.

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None.

DATA AVAILABILITY

All datasets generated or analyzed during this study are included in the manuscript.

ETHICS STATEMENT

Not applicable.

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